Space Universities Network

Supporting the Space Higher Education Community

Title (Max 10 words)

Astrodynamics Mission Simulation – University of Leicester

Summary (Max 100 words)

The University of Leicester have run an Astrodynamics Mission Simulation 10-credit module over 8 weeks (2 full afternoon computer lab sessions per week) using NASA's General Mission Analysis Tool (GMAT). The module is taught using a Constructivism approach, in which students are found to be more likely to recall and understand concepts which they have discovered independently, than those taught directly. The 30-35 students are set problem questions over the 8-week period and are supported through these in the computer lab sessions by the lecturer and post-graduates. The module is concluded with a mission scenario given to teams of 4 or 5 where students build on the knowledge acquired in the taught elements and apply them to the design of a mission. E.g. plan a mission to Mars using the Phobos-rendezvous using minimum delta V.

Figure 1 – General Mission Analysis Tool (GMAT) [Image credit: gmatcentral.org]

Aims/Objectives

The Astrodynamics Mission Simulation module is designed to enhance career options in industry, education, research and business. The intended learning objectives are as follows:

- derivation of Kepler's problem & solutions
- orbital manoeuvres & transfers
- perturbations
- initial orbit determination
- Lambert's Problem
- interplanetary trajectories
- B-plane targeting

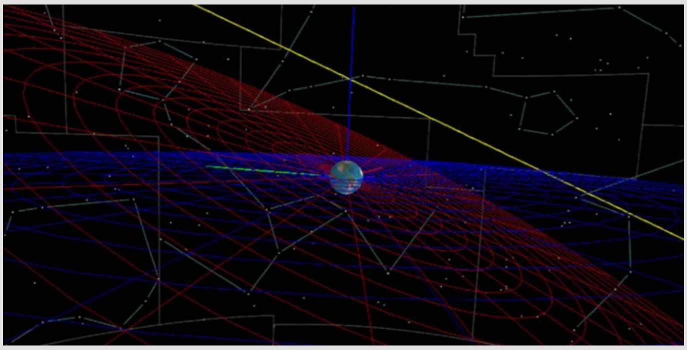

Figure 2 – GMAT screencast displaying a Vernal equinox [Image credit: Bannister, 2018].

What was the context / background?

Astrodynamics is the study of spacecraft artificial satellite motion, subject to both natural and artificially induced forces. It combines celestial mechanics, attitude dynamics and aspects of positional astronomy to describe spacecraft motion and enable the planning and analysis of missions.

The Astrodynamics Mission Simulation module is associated with a third-year undergraduate module comprising 12 lectures and screencasts providing an introduction to astrodynamics. This Astrodynamics lecture module is not a prerequisite to the Mission Simulation module however both are very complimentary (approximately 80% of students take both modules). The Mission Simulation module is designed to be accessible to students that are not taking the associated Astrodynamics lecture module.

How was it organised and who was involved?

This was a staff-led curricular module. The module was run over an 8-week period with 2 full afternoon computer lab sessions per week. The first 2 sessions were run as step-by-step tutorials. The process undertaken to set up this module was as follows:

- Module director was already proficient in the use of GMAT before founding the module.
- Student employed over a Summer to work in partnership with the module director to put together a workbook from which classes are run. The student had completed the final year of their BSc and was one of the stars of the taught astrodynamics module.
    - It is estimated that somebody working roughly a month full time would be able to set up a basic problem question to start a module like this from scratch.
- Classes are run for between 30 and 35 students.
- These are supported by the module director and 1 post-graduate, although it is planned to have 2-3 post-graduates in future.
    - Post-graduates go through the workbook themselves as preparation for the role. Some are not familiar with GMAT, others have some familiarity. It helps to have continuity – it takes time for the facilitators to become proficient in the role, so it helps to have post-graduates over 2 seasons.
- The first two sessions are run as step-by-step tutorials where the lecturer will take the students through the activity in detail to familiarise the class on the use of GMAT.
- Subsequent sessions are done without tutorials where students follow activities set out in the workbook. In these sessions, going ‘off-piste’ is encouraged – student experimentation and perturbation can lead to the discovery of interesting results which are used to fuel class discussion. A full list of the 11 problem scenarios that make up the assessed components of the module can be found in Figure 3.
- Final activity is done in groups of 4 or 5 where a mission scenario is set. Students build on the knowledge acquired in the taught elements and apply them to the design of a mission.

Mission	Description	Marks
Polar Orbit	Simple closed orbit & exploration of basic keplerian laws, R2BP.	2
Sun Synchronous Orbit	Introduction of perturbations, J2 effect.	2
Geosynchronous Orbit	Exploration of east-west drift, stable/unstable points & drag paradox; reference frame choices.	3
Critically Inclined Orbit	Precession of the argument of periapsis, generation of Molniya orbits	3
Hohmann Transfer	Introduction to propulsive manoeuvres, orbit transfers and goal seeking.	2
Bielliptic Transfer	Demonstration of Oberth Effect; deep space transfers which exceed Hohmann transfer efficiency.	3
One Tangent Transfer	Introduction to flight path angle; fast transfers; ΔV versus transfer time.	5
Inclination Change	Introduction to out-of-plane manoeuvres. Multiple goal seeking.	4
Combined Inclination & RAAN Change	Identification of common points in orbits; efficiency of sequences vs single manoeuvres.	5
Aerobraking	Planetary atmosphere models; atmospheric drag; apoapsis lowering manoeuvres; planetary capture; entry corridors.	5
Gravity Assist	Hyperbolic orbits; introduction to gravitational assist manoeuvres; relationship between eccentricity, periapsis and turning angle.	6

Figure 3 – Problem scenarios which make up the assessed component of the module. [Image credit: Bannister, 2018]

What resources did you need?

Software

- GMAT (open-source software available here).
    - GMAT has an extensive set of help documents as well as an active user forum and YouTube videos that may be used to aid student learning.

Human resources

- 2-3 post-graduates.
- 2 full afternoons a week of support from module director.
    - The module is very supervision-heavy. Particularly in the first couple of weeks, students need a lot of support.
    - Following this initial period, module director can play a smaller role, with sessions facilitates by the post-graduates.
- 2-3 academic staff to be on the judging panel during the Mission Presentation morning.

Learning environment

- Projector screen
  - All students must have a good line of sight to the projector screen. The screen was used for the walk-through support in the first two sessions as well as student results in later sessions.
- Network-connected projector
  - A network-connected projector allowed for students to share the results of their models with the wider group at the invitation of the tutor.
  - This feature lead to lively interactions between students when unexpected effects were observed in simulations due to calculation error or physical effects that had not been considered.
  - Where mistakes were made in the configuration of a simulation, the resulting behaviour revealed interesting behaviour which merited the attention of the rest of the cohort.

Describe the activity (Max 1000 words)

The University of Leicester Astrodynamics Mission Simulation module consists of 6 stages:

1. Walk-through tutorial sessions
2. Introducing Simple Celestial Mechanics
3. Increasing Detail: Perturbations
4. Manoeuvres & Targeting
5. Advancing Beyond Earth
6. Workshop Assessment & Final Challenge

1. Walk-through Tutorial Sessions

- The academic tutor and students begin by creating a blank GMAT model.
- The tutor shows their GMAT session on the projector screen and demonstrates how to create an elliptical orbit around Earth which the students replicate on their own machines.
- The tutor can use this time to explain the architecture of the user interface in the context of a practical example.
- Time is taken at this stage to discuss the following (seen in Figure 4):
  - The trajectory equation (1)
  - The vis-viva equation (2)
  - The equation for eccentricity (3)

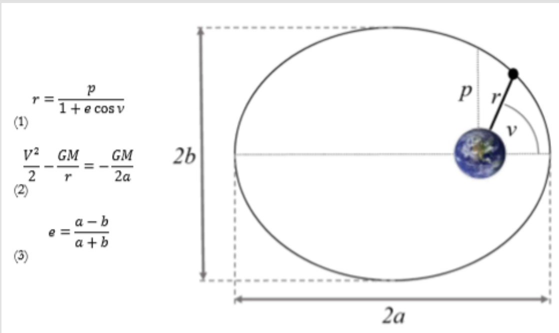

Figure 4 – The basic geometry of a closed orbit [Image credit: Bannister, 2018].

2. Introducing Simple Celestial Mechanics

- Following the walk-through sessions, the students are presented with a few problem scenarios.
- The first problem scenario involves implementing a polar Earth orbit with specific requirements on the size, shape and orientation of the orbit.

- Students are required to verify that the velocity of the spacecraft at apoapsis (the point in the orbit which is furthest from the planet) is in accordance with predictions.
- For further detail, see Analysis Case Study 1 in the Appendix.

3. Increasing Detail: Perturbations

- Exercise 1 uses the restricted two body problem to help students gain familiarity with GMAT. This assumes that the spacecraft is only subject to the force of gravity and that the gravitational field is perfectly radial.
- In reality, atmospheric drag, several sources of gravity (e.g. the Earth and the Moon), and gravitational fields that are not perfectly radial (due to real planets not being perfectly spherical or uniformly dense) affect the trajectory of a spacecraft.
- A significant consequence of Earth's non-sphericity on spacecraft orbit is a perturbation caused by the fact that the Earth is oblate (equatorial diameter is larger than polar diameter due to the planet's rotation).
- Sun-synchronous orbits are used as an example of how relaxation of the restricted two body problem assumptions can lead to more complexity.
- For further detail, see Analysis Case Study 2 in the Appendix.

4. Manoeuvres & Targeting

- Propulsive manoeuvres are enabled in GMAT by adding "Hardware" (fuel tanks and thrusters) to the spacecraft and adding "burns" which use the hardware to change velocity.
- The manoeuvre used to introduce this topic is the Hohmann transfer in which an elliptical orbit is used to transfer between two circular orbits in the same plane. The transfer orbit's apoapsis is coincident with the higher circular orbit and the periapsis matches the radius of the lower circular orbit.
- A tutorial on designing a Hohmann transfer using GMAT can be used here.
- Next, the students are given another manoeuvre problem – an orbital inclination change.
- Further detail can be found in Analysis Case Study 3 in the Appendix.

5. Advancing Beyond Earth

- Much of the module focuses on Earth-orbit however, the final phases introduce topics relevant to interplanetary missions. (GMAT includes data for the major planets along with Pluto and Earth's moon – other bodies may be added using NASA's SPICE system).
- Considerable preparation is needed before complex interplanetary trajectories can be built in GMAT, however exploring relevant concepts is within the scope of the workshop.
    - Spacecraft initial states can be given in terms of the arrival direction, energy and distance of closest approach in the frame of the destination planet.
    - Hence, students can investigate the geometry and energetics of a gravity assist manoeuvre, without the need to calculate a trajectory from the Earth to their chosen planet.
- Problem scenarios at this stage in the workshop are less prescriptive than they were at the beginning, given the students' familiarity with the system over the course of the module.
- In the specific case of gravitational assist manoeuvres, students are asked to carry out an investigation of planetary encounters, using GMAT to demonstrate underpinning concepts and verifying the results quantitatively.

- Further detail can be found in Analysis Case Study 4 in the Appendix.

6. Workshop Assessment & Final Challenge

- Formative assessment is done in two phases:
  - The student's work on each of the problem scenarios is assessed in real time – the student demonstrates their solutions and discusses their approach and understanding with a facilitator (70% of overall mark).
  - Final challenge – cohort divided into groups of 4 or 5 students. Students introduced to an extended problem in which they have ~4 weeks to study without tutor support – this is assessed during a Mission Presentation morning where each group presents their solution to the rest of the class and a panel of 2-3 academic staff (30% of overall mark).
- Examples of previous final challenge topics:
  - A Phobos sample-return mission, calculating trajectories to/from Mars, and a series of rendezvous operations in Mars space allowing spacecraft to land on the moon Phobos then return to Earth.
  - Studying and reproducing specific Apollo missions to explore the difference between the various trajectories used in the Moon programme, understanding the need for trajectory correction manoeuvres and comparing actual flight data (for e.g. burn times, directions, re-entry locations) with the predictions of the student's GMAT scenario. This challenge ended with a final stretch goal to design an Apollo-like transfer for the present day, testing student's ability to apply techniques to find new solutions, rather than relying on historical parameters known to give the required behaviour.
- During the Mission Presentation morning, PowerPoint slides are prohibited as presenting directly from GMAT (and supporting analysis in MATLAB and Excel) is more interactive than presenting snapshots in a slideshow, allowing "what if" questions to be explored in the session.
- Effective use of this presentation style is a transferable skill and a specific learning outcome of this activity.

References

Bannister, N. P. (2018). Active Learning in Physics, Astronomy and Engineering with NASA's General Mission Analysis Tool. Journal of Learning and Teaching in Higher Education, 1 (1)

Has it been evaluated? What feedback have you had?

- The majority of respondent's feedback was positive (as can be seen in Figure 5).
- In response to the question "How would you suggest the workshop could be improved?", the most common response was to increase the number of walkthroughs and increase the number of contact sessions.
- Insufficient data are currently available to determine whether use of GMAT is leading to a significant long-term improvement in examination results for the conventional astrodynamics module, but adoption of this interactive course has enabled students to explore and test the relationships developed in texts and lectures in a way that cannot be matched in more conventional teaching sessions, helping students to make meaning in their studies. From this perspective alone, introduction of GMAT as a core learning tool has been of substantial benefit.

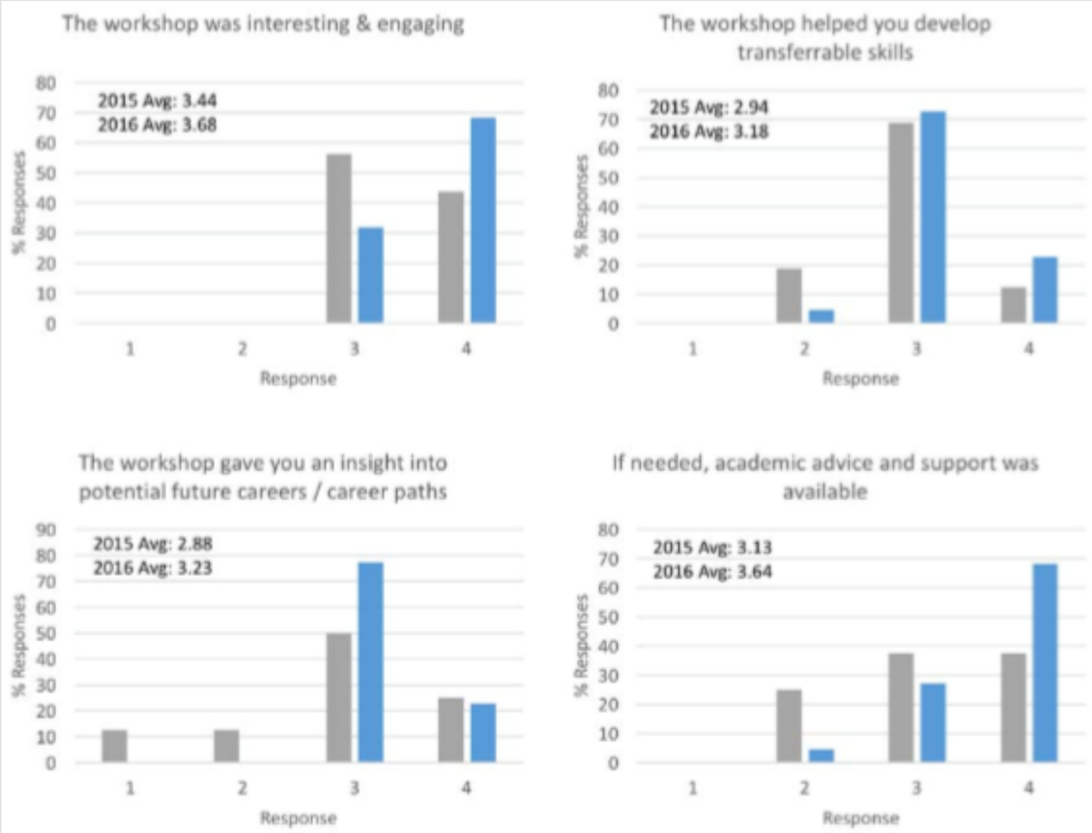

Figure 5 - Feedback from students at the end of the 2015-16 (grey) and 2016-17 (blue) sessions, normalised to the total number of respondents in each year (16 in the 2015-16 session, 22 in 2016-17). Responses correspond to “Definitely Disagree” (1); “Mostly Disagree” (2); “Mostly Agree” (3) and “Definitely Agree” (4). [Image credit: Bannister, 2018]

Key Learning Points

There were some significant lessons learned:

- Changes made between the 2015 pilot and 2016 course have led to improvements in satisfaction in each of the 4 areas (as can be seen in Figure 5). Changes included:
    - The introduction of “walk-through” sessions to help the students gain familiarity with the basic software architecture.
    - Short breakout sessions to cover specific astrodynamics concepts in a more lecture-like form.
    - Final year PhD student facilitator to increase the level of support available.
- Synchronisation with taught modules
    - Timing of activities must be planned carefully to ensure that prerequisite knowledge is accessed by the students before using the simulations.
- Do not over-estimate the pace of progress through the workshop
    - The use of simulation requires time for the students to become familiar with the software. This overhead is greatest at the beginning but is present throughout the duration of the workshop.
- Test thoroughly before deployment
    - Adequate preparation and bug testing of the workshop (preferably with the use of a volunteer who may make the same mistakes as a student) can identify these issues, and workshop instructions can be updated to avoid the problem disrupting the taught sessions.
- Simulation is not a replacement for conventional learning methods
    - Simulation alone cannot replace the effort needed to understand the scientific principles

underpinning the system being modelled. Without understanding of the scientific principles, using GMAT simulations are little more than an exercise in entering numbers into a black box.

Thematic Categories (tick any that apply to your case study)

Method		Topic	
Online Text and Notes	☐	Orbits and Trajectories	☒
Assessment Materials	☐	Rocket Propulsion	☐
Video and Audio Lectures	☐	AOCS/ADCS	☐
Lecture Slides	☐	Payloads	☐
Curricula	☐	Power	☐
Video and Audio Clips	☐	Communications	☐
Recommended textbooks	☐	On Board Data Handling	☐
Useful software	☒	Systems	☐
Worksheets and Projects	☐	Mechanical	☐
Simulations	☒	Thermal	☐
Tutors' Guides	☐	Astronomy	☒
	☐	Earth Observation	☐
	☐	History of Spaceflight	☐
	☐	Other	☐

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